J. Physiol. (1980), **302**, *pp.* 427–441
With 6 *text figures*
Printed in Great Britain

COMPARISON OF ELECTROMYOGRAM SPECTRA WITH FORCE SPECTRA DURING HUMAN ELBOW TREMOR

By P. B. C. MATTHEWS and R. B. MUIR*
From the University Laboratory of Physiology,
Parks Road, Oxford OX1 3PT

(*Received 4 September 1979*)

SUMMARY

1. The tremor that develops when the elbow is flexed against a spring attached at the wrist has been analysed by determining the 'power' spectrum of the demodulated surface e.m.g. recorded from two of the active muscles, biceps and brachioradialis. This was compared with the corresponding force spectrum obtained by analysis of the force developed at the fixed end of the spring (normally one of stiffness 2·8 N/mm); this force is directly proportional to the movement at the wrist.

2. When the subject was maintaining a high target force (100–160 N), with the aid of a visual display, the tremor was large with a large sharply tuned peak in the force spectrum and there was a clear peak at the same frequency in the e.m.g. spectrum. The coherence (γ) between the force peak and the corresponding e.m.g. peak typically had a value of 0·95 or above, indicating a high degree of correlation.

3. On developing the same target force against a rigid restraint (70 N/mm) the peak in the force spectrum was absent or very much smaller and less sharply tuned. More particularly, the tremor-related peak seen in the e.m.g. spectrum under compliant conditions was no longer present under rigid conditions.

4. At low target forces (20–40 N) with compliant loading there was a small peak in the force spectrum but no peak could be detected in the e.m.g. spectrum. With increasing target force the mechanical tremor increased considerably and a peak progressively emerged from above the background level in the e.m.g. spectrum, accompanied by the development of a corresponding peak in the coherence spectrum. Thus the difference in detectability of peaks in the e.m.g. and force spectra might simply result from differences in the background 'noise' level of the two types of spectra.

5. Changing the spring stiffness in the range 0·7–12·5 N/mm altered the frequency of the mechanically recorded tremor by 1·5–2 Hz and the peak in the e.m.g. spectrum shifted in approximate correspondence.

6. The findings support the view that the tremor seen with compliant loading of the arm is due to the stretch reflex. In addition, this work should help define the conditions under which spectral analysis of the gross e.m.g. is of practical utility.

---

* Present address: Department of Anatomy, Erasmus University Rotterdam, Rotterdam, The Netherlands.

INTRODUCTION

After prolonged debate on the origins of physiological tremor, it is becoming increasingly accepted that tremor in the 8–12 Hz range may result from a variety of intereracting mechanisms, one or other of which may predominate under any particular condition (see papers in Desmedt, 1978). Small amplitudes of tremor, for example, might result simply from the unfused contractions of motor units firing randomly, and the mechanical resonance of elastic muscles loaded by mass might preferentially favour a particular tremor frequency from widely ranging motor unit firing rates. Alternatively, neural mechanisms, whether reflex or purely central, might partially synchronize the firing of different motor units to produce a rhythmicity of motor discharge. Thus, in any particular case, analysis of the electromyogram would seem potentially to be capable of providing crucial information about the occurrence of neural involvement in the genesis of tremor. Simple inspection of the gross e.m.g. suffices to demonstrate the deep modulation due to the synchronized firing of large numbers of motor units that is sometimes seen pathologically, but has not proved fruitful in the analysis of most physiological tremor. Spectral analysis of the e.m.g. after rectification provides a more objective way of deciding whether or not there is rhythmic electrical activity associated with mechanical tremor and has now been used in several studies, for example that by Elble & Randall (1976). A peak may be produced in the e.m.g. spectrum either by motor units actually firing at the tremor frequency or by the modulation at this frequency of higher rates of motor firing. The present work further explores the applicability of spectral analysis by using it to study the tremor that develops when a subject exerts force against a spring by flexing his elbow. Such tremor was analysed with mechanical recording by Joyce & Rack (1974) who showed that when the subject pulled hard he developed a tremor of up to 5 mm peak-to-peak extent at the wrist.

Joyce & Rack interpreted the tremor seen with compliant loading of the arm in terms of the coupling of two resonators, one being neural and provided by the timing of the stretch reflex arc and the other being mechanical and provided by the mass of the arm (with its attachments) acting into the elasticity of the spring together with that of the muscle. The main evidence for the involvement of the stretch reflex came from companion experiments in which Joyce, Rack & Ross (1974) found that when a small sinusoidal movement was imposed on the arm while the subject was exerting a high mean force then the stretch reflex led the arm to show a 'negative viscosity' at certain frequencies, thus making the development of tremor almost inevitable when the limb was loaded appropriately. Our experiments lend support to their view by demonstrating the presence of a clear peak in the e.m.g. spectrum when the arm is exhibiting vigorous tremor during compliant loading. Further, the absence of such an e.m.g. peak when the arm was restrained rigidly shows that the development of the phased neural activity in the compliant situation requires feedback from the movement of the limb. At low levels of exertion against a spring a tremor was still observed but a peak was no longer detectable in the e.m.g. spectrum, possibly simply because of an appreciable noise level in the e.m.g. and not necessarily because the origin of the tremor had changed. More generally, it is argued that the absence of an appropriate peak in an e.m.g. spectrum cannot be adduced as evidence against the participation of rhythmic neural activity in a tremor (cf. Fox & Randall, 1970) until the sensitivity of the method has been assessed in each particular situation. The present techniques have been demonstrated to the Physiological Society (Cussons, Matthews, Muir & Watson, 1978).

METHODS

Eleven healthy human subjects aged 17–45 years took part in the experiments; one was female, ten male.

Mechanical apparatus. The subject sat beside a solid concrete table which carried the mechanical apparatus. A rigid platform supported the elbow of the subject's bared right arm at a height such that the upper arm was approximately horizontal. Flexion force about the elbow was resisted by a light-weight harness on the forearm just proximal to the wrist. The harness consisted of a piece of sturdy aluminium extrusion 10 cm long and 5 cm wide attached at either end by multi-strand steel wire to a common link which could be connected, either directly or via any of a variety of helical steel springs, to a rigidly mounted, stiff beryllium copper blade, bearing strain gauges for force transduction. A padded steel bar positioned firmly against the anterior aspect of the subject's right shoulder served to stabilize the shoulder during elbow flexion. For each particular combination of spring compliance and flexion force the position of the force transducer mounting was adjusted so that the subject's forearm was vertical when the correct force was produced (thus the elbow angle was approximately 90°).

The stiffness of each spring, with the harness and force transducer, was determined under static conditions. The stiffness ranged from a maximum of 70 N/mm with no interposed spring to 0·7 N/mm with the most compliant spring; the other values were 1·4, 2·8, 6·1, 12·5 and 25 N/mm. The masses of the springs were all low compared with that of the forearm; the values in order of increasing stiffness were 65, 160, 80, 13, 6 and 3 g and the mass of the harness was 88 g. The behaviour of each spring under dynamic conditions was investigated with the spring attached to the force transducer while the harness at the other end of the spring was displaced sinusoidally at constant amplitude by an electromagnetic driver. For all the springs used the recording from the force transducer was in phase with the displacement and of constant amplitude (to within 5%) for frequencies up to 15 Hz. In other words, in this frequency band values of recorded force may be transmuted into displacement at the wrist by using the static calibration of spring stiffness as the conversion factor.

Force recording. The electrical output of the strain gauge bridge was amplified, low-pass filtered (50 Hz), then recorded on one channel of FM magnetic tape (0–300 Hz) and displayed on a monitor oscilloscope positioned approximately 50 cm in front of the subject (display gain usually 0·75 mm/N). A further stage of amplification was combined with a clamp circuit which held the 'high gain' output constant at a preset voltage until about 6 sec after the subject had brought the force up to the required level, and thereafter, until the sampling period was completed, registered only the deviations from the force at the instant of unclamping. The relevant segments of high gain force signal could thus be recorded on a second FM tape channel without risking saturation, while still preserving full gain at low frequencies. A band-pass filter flat to within ± 1 db from 1·5 to 23 Hz limited the frequency content of the high gain force signal appropriately for sampling by a PDP 12 computer which stored the digitized values on magnetic disk and subjected them to spectral analysis.

E.m.g. recording. The surface electromyogram of m. biceps brachii and in most experiments also m. brachioradialis was recorded using plastic disk electrodes (Devices; diameter 35 mm) fixed by double-sided adhesive tape, with electrical connexion to the skin effected by electrode jelly. In each case the two recording electrodes were positioned longitudinally over the central region of the contracted muscle belly with a centre-to-centre spacing of approximately 35 mm, and a third identical electrode, fixed just lateral to and equidistant from the recording electrodes, served as an earth connexion. Differential amplifiers of bandwidth 10 Hz–10 kHz were located close to the subject's arm permitting the e.m.g. leads to be kept short to minimize electrical interference. After amplification each e.m.g. signal was high-pass filtered (25 Hz) to remove any low frequency artifacts directly associated with the tremor movements, then full-wave rectified and low-pass filtered (25 Hz) to give a smoothed signal referred to as the 'demodulated' e.m.g. (Fox & Randall, 1970). Fig. 1 illustrates these successive stages of processing. Usually the demodulated e.m.g.s from both muscles were recorded on FM tape, but that of only one muscle could be accepted by the computer concurrently with the force signal; the second demodulated e.m.g., reproduced from magnetic tape, was analysed at a later time. Band-pass filtering and computer analysis identical with that used for the force record was applied to the demodulated e.m.g. signals.

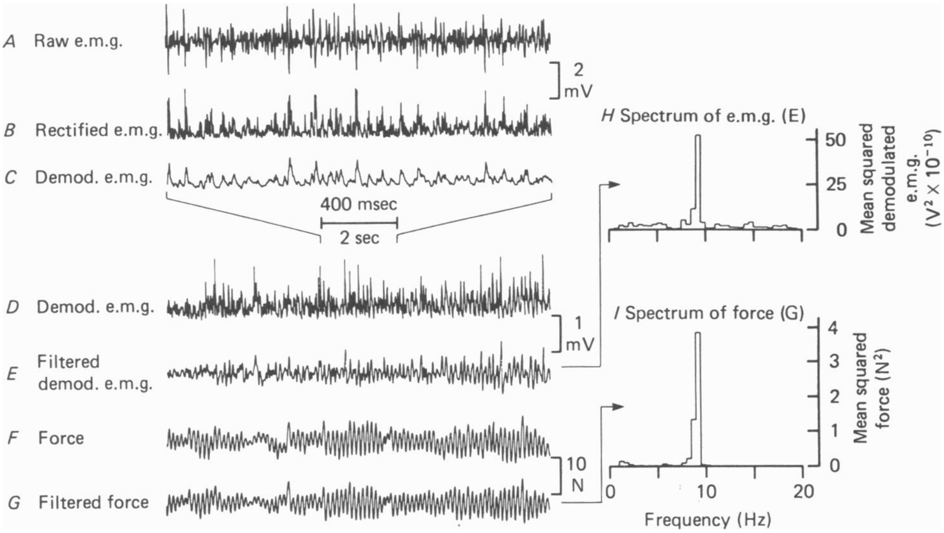

Fig. 1. Sample records illustrating the successive stages of data processing in obtaining tremor spectra. The subject was exerting a mean force of 140 N by flexing his elbow against a spring of stiffness of 2·8 N/mm. *A*, 2 sec segment of the gross e.m.g. recorded with surface leads over biceps (bandwidth, 10 Hz–10 kHz); *B*, after high pass filtering (25 Hz) and full-wave rectification; *C*, after transmission through a low-pass filter (25 Hz) to give the 'demodulated' electromyogram; *D*, 10 sec segment of demodulated e.m.g., including the 2 sec segment of *C* as indicated; *E*, after band-pass filtering (1·5–23 Hz) preparatory to computer analysis. *F*, 10 sec segment of high gain force record obtained concurrently with the e.m.g.; *G*, force after band-pass filtering as for *E*. *H*, 'power' spectrum for the 10 sec segment of filtered demodulated e.m.g. *I*, corresponding force spectrum. Subject, F.J.C.

Experimental procedure. The subject was instructed to pull on the harness with the forearm fully supinated until the spot on the monitor oscilloscope coincided with a line on the graticule which indicated achievement of the required target force, and thereafter to attempt to hold the spot as precisely as possible on the line until instructed to relax. If tremor occurred, the subject was to concentrate upon trying to keep the slightly elongated spot centred on the target line. Following the command to pull, a 6 sec delay ensured that the subject had time to stabilize at the target force before the amplifier was unclamped in readiness for sampling which commenced a further 0·5 sec later. After pulling for approximately 17 sec altogether the subject rested for 1 min or more before the next start command was issued.

Spectral analysis. During each period of attempted steady elbow flexion, the computer sampled the filtered high gain force and filtered demodulated e.m.g. signals for 10 sec, at a sampling rate of 51·2 Hz, giving 512 digitized values for each signal. Each record was then adjusted to have zero mean and subjected to a data window consisting of a half-cosine bell applied to the first and last 10% of the data values (Bingham, Godfrey & Tukey, 1967). Fourier analysis was performed using a fast Fourier transform algorithm (Brigham & Morrow, 1967) and the squared magnitude for each 0·1 Hz bin was calculated. To obtain spectra of greater statistical reliability, frequency smoothing was performed by adding together consecutive bins of the raw spectra in groups of five, and a number (usually four) of such smoothed spectra obtained from different 10 sec samples recorded under the same conditions were averaged (Bendat & Piersol, 1971). The resulting spectra, with a bin width of 0·5 Hz, were calibrated by applying the same analysis procedure to steady sinusoidal signals of known equivalent mean squared amplitude.

To investigate the degree of linear relationship between tremor in the force record and any similar fluctuations of the demodulated e.m.g. (as suggested by corresponding peaks in the force and e.m.g. spectra) the coherence spectrum was calculated (Bendat & Piersol, 1971). Here again frequency smoothing and segment averaging were performed on the 'power spectra' and 'cross-power spectra' before determining the values of coherence (γ).

Although all spectra were calculated over the frequency range 0–25·6 Hz, spectra shown in the Figures have been truncated at 20 Hz since spectral bins at higher frequencies almost always have negligible content. It should be noted that the three bins between 0 and 1·5 Hz in all spectra have had their values attenuated by the action of the analogue filter and no correction has been made for this effect; however all spectral bins above 1·5 Hz may be taken at face value since all amplification was essentially flat from 1·5 to above 20 Hz.

RESULTS

Whenever a subject maintained a moderately strong flexing force with the wrist restrained compliantly by a relatively compliant spring (routinely 2·8 N/mm static stiffness) then there was a vigorous tremor which was readily visible to an observer, as described by Joyce & Rack (1974). Spectral analysis of the accompanying rhythmic force oscillations yielded a sharply tuned tremor peak. But when the same mean force was exerted against a rigid restraint, although the high-gain force record still exhibited considerable variability, the force fluctuations showed little or no rhythmical component and no well tuned tremor peak was evident in the spectrum. These essential observations are illustrated in Fig. 2 along with the corresponding findings for the electromyogram. The top traces of Fig. 2*A* show a 10 sec record of filtered force obtained during compliant restraint together with an equivalent record taken under rigid conditions from the same subject with the same target force. Immediately beneath these records are the corresponding traces of the filtered demodulated gross e.m.g. obtained from the biceps muscle with surface recording; in essence, demodulation provides the smoothed envelope of the original e.m.g. Under compliant conditions the e.m.g. record shows rhythmical fluctuations at the same frequency as the tremor in the force record. Moreover, although there was no strict one-to-one relationship, close examination of the same data displayed on an expanded time scale revealed a more or less constant phase relationship between the large components of rhythmic tremor in the two types of record. In contrast, little or no rhythmicity was apparent on visual inspection of the corresponding force and e.m.g. records obtained under 'isometric' conditions.

Spectral analysis of the records of Fig. 2*A* together with, in each case, three similar 10 sec segments of data obtained from the same subject under the same conditions yielded the spectra shown in Fig. 2*B*. During compliant loading of the arm the tremor contributes prominent and sharply tuned peaks at the same frequency in both the force and the e.m.g. spectra. The root-mean-squared (r.m.s.) force over the 6–12 Hz band was 1·9 N and almost all of this force fluctuation is concentrated in the 1·5 Hz between 10·0 and 11·5 Hz. This corresponds to an r.m.s.

movement at the wrist of 0·7 mm and an average peak-to-peak movement of nearly 2 mm. There is also a peak in the coherence spectrum at the tremor frequency where γ reaches a maximum of 0·95 (a γ of unity indicates a linear noise-free relation). This establishes that there is indeed a close correlation between the moment to moment rhythmical fluctuations in the demodulated e.m.g. and those in the concurrently recorded force recording; moreover, the association is so strong that a functional relationship must be presumed to exist between the e.m.g. and the force at the tremor frequency.

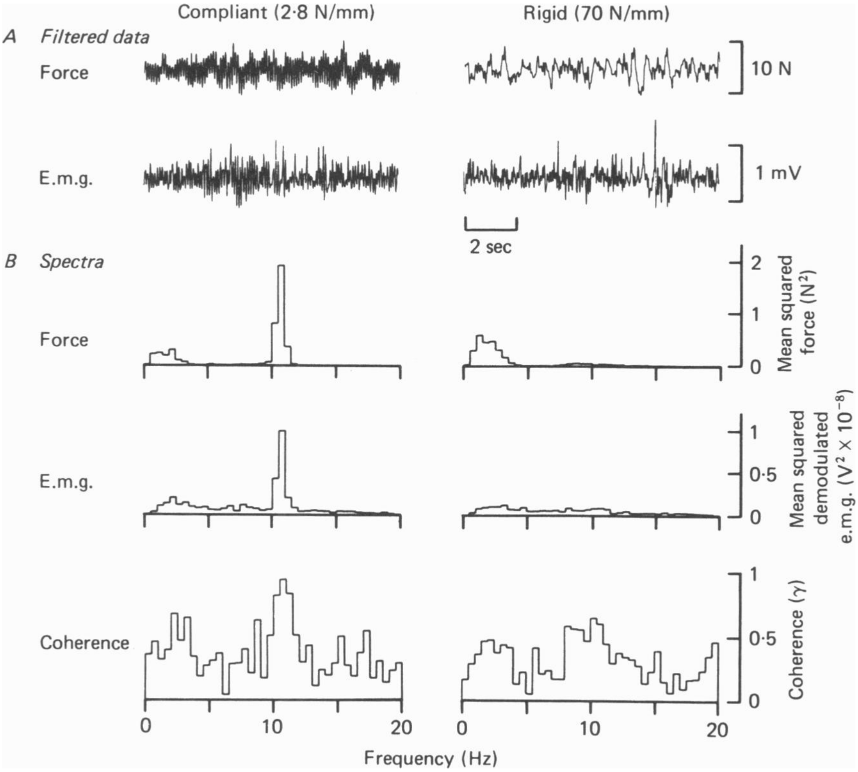

Fig. 2. Dependence of tremor upon the mechanical loading of the arm with a tremor peak in the spectra both of force and of biceps e.m.g. when the subject was flexing his elbow against a spring (left), but not when the arm was anchored rigidly (right). *A*, 10 sec segments of filtered data (force and demodulated e.m.g., cf. Fig. 1). *B*, spectra from these and a further 30 sec of recording obtained under the same conditions. With compliant loading, the coherence between the force and the e.m.g. rises to a value of 0·95 at the peak tremor frequency. Mean force, 120 N. Subject, W.L.L.

On the other hand, the force spectrum for rigid attachment of the wrist shows only the slightest hump around 10 Hz and plotting the spectra on higher gain showed that it was much more broadly tuned than that seen under compliant conditions and the half-power band spread from 7·5 to 11·5 Hz; however, the r.m.s. value over the range 6–12 Hz was still 0·7 N (note that the spectra show squared values). There is an increase in the spectral components below 5 Hz which is thought to be related to the commonly reported subjective experience that it is more difficult to keep the mean force at its target value under rigid conditions than with flexible attachment of the arm. The spectrum of the demodulated e.m.g. for rigid loading shows no tremor peak, even though the biceps muscle can be presumed to have been activated to the same degree as during compliant loading, since the mean flexor force at the wrist was the same in both cases. Moreover, the tremor peak in the e.m.g. spectrum for compliant loading has a substantially higher r.m.s. content than the corresponding bins in the e.m.g. spectrum for rigid loading, thus leaving little doubt that the greater tremor seen under compliant conditions results from an additional active neuromuscular contribution at the tremor frequency.

Such findings were typical for all eleven subjects. On flexing against the standard spring (2·8 N/mm) with a high mean force all showed a clearly recognizable peak in the e.m.g. spectrum of biceps and the peak was at the same frequency, to within 0·5 Hz, as that in the force spectrum. Likewise a peak at the tremor frequency was seen in the spectrum of the e.m.g. from the brachioradialis muscle for the eight of the subjects in whom this was studied; brachioradialis is equally a flexor of the elbow and could be seen to be contracting strongly. Usually, the coherence between force and e.m.g. was determined for the e.m.g. of one only of the muscles. The maximum values ranged between 0·88 and 0·97 for the eleven subjects of whom eight showed coherences of 0·95 or above. Thus when the tremor is vigorous there is invariably electromyographic activity that is significantly correlated with the mechanically recorded tremor. Under isometric recording conditions at comparable mean forces tremor peaks could not be detected in the e.m.g. spectra of either biceps or of brachioradialis in any of the nine subjects who were studied in this respect.

The force spectra obtained with rigid loading never showed a peak that was comparable in magnitude to that seen with compliant loading and never one that was sharply tuned with most of the power in the range 6–12 Hz falling within one to three bins. However, increasing the amplification of the spectra quite frequently showed small rather flat spectral humps in the range 6–12 Hz rising above the values at 4–6 Hz, as was the case in the experiment of Fig. 2. In assessing the significance of such observations it should be remembered that when the arm was restrained 'rigidly' there was still a certain amount of compliance in the connexions (stiffness 70 N/mm) and there will have been further compliance in the relevant tendons and in the soft tissues at the wrist.

It must be noted that the above arguments would be invalidated if the peak in the e.m.g. spectrum at the tremor frequency were to be attributable to some kind of movement artifact. The e.m.g. peak cannot be due to any cyclic potential at the tremor frequency that may be present in the raw e.m.g. since this would have been eliminated by the initial high-pass filtering. But such filtering would not remove the effects of any cyclic change in the efficacy of recording arising from movement of the muscle relative to the electrodes which might lead to an amplitude-modulation of the higher frequency components of the e.m.g. at the tremor frequency; in other words, the size of the potential recorded on the discharge of a given motor unit might vary with the phase of the tremor cycle. The existence of any significant contribution from such a movement artifact was discounted by the following observations. First, in a control experiment on the subject of Figs 1 and 4 the skin over biceps with its attached electrode assembly was oscillated at 10 Hz with a peak-to-peak movement of about 1 mm while the subject was making a steady contraction against a rigid attachment, and the usual spectral analysis was performed.

No e.m.g. spectral peak was then detectable, although the relative movement of the electrodes and the muscle was judged to be several times greater than that occurring while the subject was developing tremor on exerting the same force against the standard spring, when the usual e.m.g. peak was observed. The 10 Hz skin movement was produced by an electromechanical driver pulling upon a string which was attached with adhesive tape to the e.m.g. electrodes on the subject's arm. Secondly, in related experiments on the effect of muscle vibration on tremor (Cussons *et al.* 1980) it was noted that the same amount of mechanical tremor might be associated with very different sizes of e.m.g. spectral peak for a particular muscle, depending upon whether biceps or triceps was vibrated. Moreover, for a given level of tremor, changing the locus of vibration increased the e.m.g. peak for one muscle while decreasing it for the other. Thus the sizes of the e.m.g. peaks can be dissociated from the magnitude of the tremor.

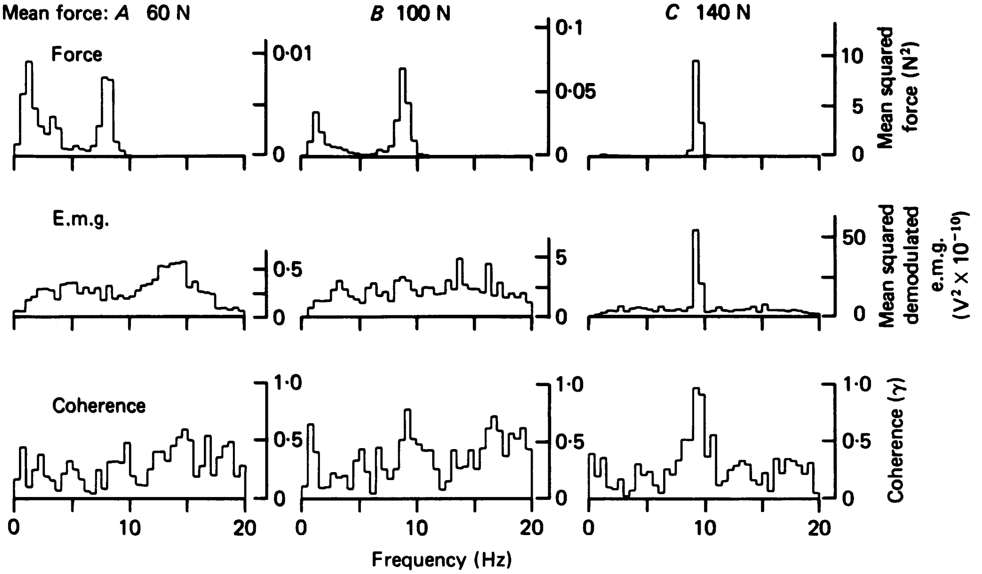

Fig. 3. Spectra obtained with compliant loading at three different target forces illustrating the increase of tremor with force and the emergence of an e.m.g. peak and a coherence peak. Note the progressive change of scaling from left to right, and the change in tremor frequency. Spring stiffness, 2·8 N/mm. E.m.g. recorded from biceps. Subject, F.J.C.

Emergence of e.m.g. peak with increasing mean force

Joyce & Rack (1974) showed that the amount of tremor developed on flexing the arm against a given spring increased markedly with increase of the mean force exerted by the subject, until a maximum was reached for forces of half to three quarters of the subject's maximal strength. The present experiments re-iterate this observation for forces up to about half maximal and show additionally that an e.m.g. peak is only detectable when the mean force is moderately high and the tremor large, probably because it is only then that the e.m.g. peak is large enough to emerge from the background noise. Tremor was studied during compliant loading at each of three or more target forces in all subjects. The results fell into a consistent pattern. At low target forces (20–40 N) there was often a distinct tremor peak in the force spectrum, but no corresponding peak was ever observed in the spectrum of the demodulated e.m.g. for any of the eleven subjects, whether biceps or brachioradialis or both were studied. At intermediate strengths of elbow flexion (60–120 N, depending upon subject) the force tremor became appreciably greater and usually more sharply tuned and a corresponding peak began to appear above the broad-band background of the e.m.g. spectrum, though at the lower forces its recognition was a matter of considerable uncertainty. Finally at moderately high target forces (typically 100–140 N) the tremor always became large and the e.m.g. spectrum regularly showed a well defined tremor peak, as already described; usually, its sharpness of tuning was then comparable with that of the corresponding force peak. Fig. 3 illustrates this progressive emergence of the e.m.g. peak for one subject. A parallel emergence of a peak in coherence at the tremor frequency can be seen in the coherence spectra, with γ reaching a maximum level of 0·97 at 140 N target force. The lowest target force at which a distinct e.m.g. peak could be recognized varied from subject to subject over the range 80–120 N, and seemed to be positively correlated with the physical strength of the subject, although any such correlation was not studied systematically.

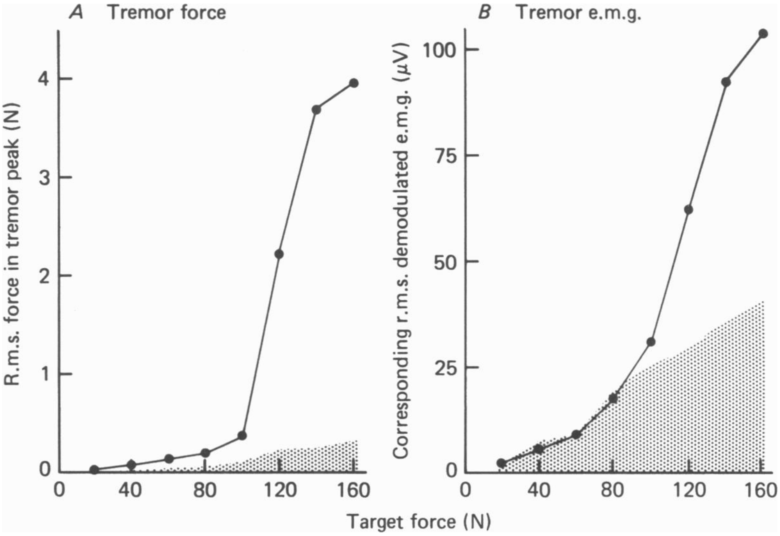

Fig. 4. The effect of increasing target force on the size of the spectral tremor peak shown graphically for the experiment of Fig. 3. *A*, the points give the root mean square (r.m.s.) value of the tremor computed from the largest three consecutive 0·5 Hz bins of the peak in the force spectrum (the tremor frequency increased with mean force, see later). *B*, r.m.s. content of the corresponding three bins of the spectrum of the demodulated e.m.g. The height of the stippling in each case shows the r.m.s. 'noise' of three average bins over the range 6–12 Hz, but excluding the three bins of the tremor peak.

Fig. 4 shows a more quantitative assessment of the development of the tremor peaks in the force and in the e.m.g. spectra for the experiment of Fig. 3. It was obtained as follows. First, the r.m.s. value of the main part of the peak in each force spectrum was calculated from the area of the three greatest consecutive 0·5 Hz bins within the 6–12 Hz band to give the points in Fig. 4*A*. The r.m.s. content of the corresponding three bins of each e.m.g. spectrum was next calculated to give the points in Fig. 4*B*; this method of selection obviated the need to identify a peak in the rather 'noisy' e.m.g. spectrum, but presupposes that it is similarly located to that in the force spectrum. Finally, the background noisiness of the spectra for each force level was estimated by calculating the r.m.s. content of three average bins of the remaining nine in the 6–12 Hz range to give the result indicated by the height of the stippling in Fig. 4. As was typical, the force peak can be seen to stand out from the background over the full range of target forces, whereas the e.m.g. peak only emerges from the 'noise' at intermediate to large target forces. The r.m.s. tremor force ranges from 0·02 N at 20 N target force to 3·9 N at 160 N corresponding to r.m.s. amplitudes of displacement at the wrist of 8 μm and 1·4 mm respectively. The non-linear form of the relationship between tremor and target force, with tremor increasing much more steeply at higher forces, was a characteristic feature although not all subjects showed as abrupt a transition from the gradual increase at low forces to the steep increase at high forces as occurred at about 100 N in the experiment of Fig. 4. The slight tendency to flattening at the top probably corresponds to the beginning of the plateau described by Joyce & Rack (1974) who also showed that at still higher forces the tremor decreases again.

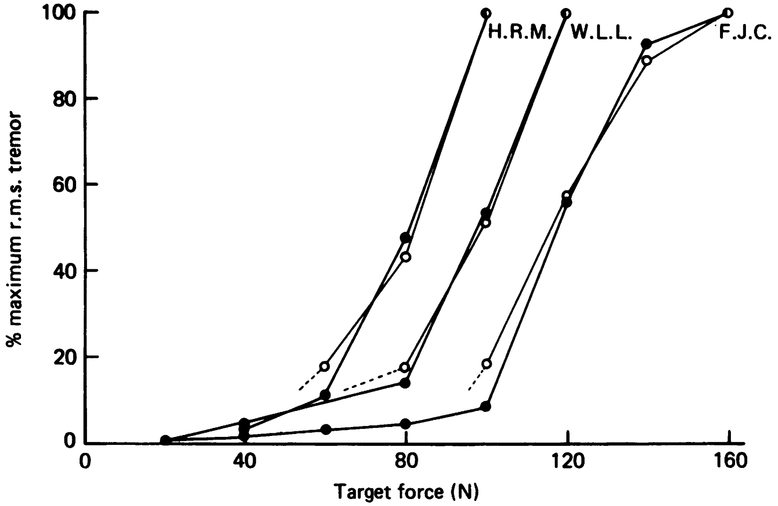

Fig. 5. The effect of increasing target force on the elevation of the tremor peak, above the noise level, in the force spectrum (●) and in the e.m.g. spectrum (○) for three subjects, indicated by initials. The value plotted in each case is the r.m.s. content of that area of the tremor peak which stands over and above the mean 'noise' at each target force, expressed as a percentage of the r.m.s. value found at the maximum force for that subject. The e.m.g. graphs have been arbitrarily discontinued below 20 % where the e.m.g. tremor peaks became indistinguishable from background 'noise'. All e.m.g.s recorded from biceps. From left to right the maximum values of r.m.s. tremor force were 3·7, 1·7 and 3·9 N; the corresponding values for the e.m.g. were 67, 118 and 95 μV, though these will have depended partly upon the precise electrode arrangement for each subject. Spring stiffness, 2·8 N/mm.

Fig. 5 shows a yet more direct comparison of the progressive parallel growth of the e.m.g. and the force spectral peaks with increase of target force for the experiment of Figs. 3 and 4 (F.J.C.) and two others. The value plotted is now the r.m.s. content of only that part of each peak which stands over and above the 'background noise' and has been normalized by expressing each value as a percentage of the maximum obtained for that subject; the two other subjects were not studied with such high target forces as those used for F.J.C. For clarity of presentation the e.m.g. curves have been discontinued arbitrarily at low target forces where any e.m.g. peak present is indistinguishable from the broad-band e.m.g. activity. It can be seen that although different subjects begin to show the steeply force-dependent tremor at different levels of target force, the emergence of an e.m.g. peak and its subsequent increase in size closely parallels the growth of the force tremor peak over the same range of target forces. A fourth subject for whom these calculations were performed showed curves similar to those of W.L.L. in Fig. 5. Thus it seems inevitable that at low target forces the background noise must hide any e.m.g. activity that may be associated with the small degree of tremor which is then present.

As already noted by Joyce & Rack (1974) tremor frequency increases progressively with increasing target force, as may be seen in Fig. 3. This was found for all ten subjects who were tested at four or more different target forces with constant compliance. Peak frequencies shifted from around 7·5–8·5 Hz at low target force (20–40 N) up to 9·5–11·0 Hz at moderately high force levels (120–160 N). At all target forces for which a clear e.m.g. peak was present, the e.m.g. peak frequency was regularly the same as the dominant tremor frequency; almost always the maximum value of the corresponding e.m.g. and force spectra occurred in exactly the same spectral bins, and only in a few instances when the tremor activity was spread almost equally between two adjacent spectral bins were the actual bins for the maximum different in frequency, and then only by one bin width.

Shift of e.m.g. peak on altering tremor frequency by varying the spring stiffness

The correspondence between the peak in the e.m.g. spectrum and that in the force spectrum was further investigated by using springs of different stiffness to alter the tremor frequency while keeping the target force constant at a moderate (usually 100 N) value. This was done for four subjects with six different stiffnesses of spring and for a further two subjects with each of three different spring stiffnesses. All subjects showed a progressive shift in the peak tremor frequency of the mechanical tremor with changing compliance similar to that already described by Joyce & Rack (1974) and by Robson (1959). The lowest frequency of tremor (typically 7–9 Hz) occurred with the most compliant spring (static stiffness, 0·7 N/mm) and as spring stiffness was increased up to about tenfold (to 6·1 or 12·5 N/mm) there was typically a progressive increase in peak tremor frequency totalling 1·5–2 Hz. At yet higher values of stiffness (12·5 or 25 N/mm) the tremor frequency tended to remain steady or even to fall slightly with increase of stiffness, although the sharpness of tuning of the peak often became too poor to allow reliable isolation of a peak frequency (cf. Joyce & Rack, 1974). The tuning of the e.m.g. peak under these various conditions was often rather worse than that of the force peak, and an e.m.g. peak did not always remain unambiguously detectable when a force peak was still evident. But when a clear peak was present in both the e.m.g. and the force spectra then the frequency of the peak in the e.m.g. spectrum invariably changed in sympathy with that in the force spectrum on altering the compliance. This is illustrated by a typical example in Fig. 6 where a fourfold change in spring stiffness has caused a 1·5 Hz shift in the peak tremor frequency for both force and e.m.g.

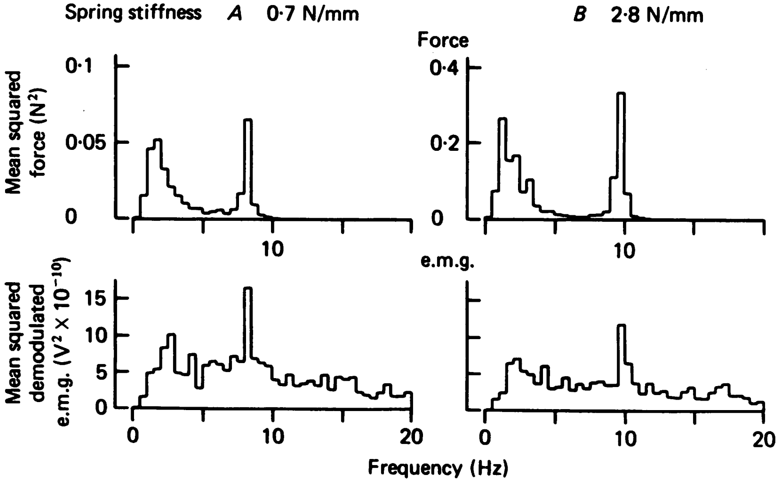

Fig. 6. Shift of the e.m.g. peak along the frequency axis on altering the frequency of the mechanical tremor by changing the stiffness of the spring against which the arm was pulling. The r.m.s. tremor *movement* was greater for the weak spring of *A* (0·48 mm) than for the stronger spring of *B* (0·22 mm), although the r.m.s. force was less. Mean force, 100 N. E.m.g. recorded from brachioradialis. Subject, E.J.W.

Throughout the six experiments, whenever there existed a single sharply-tuned peak in the e.m.g. with the half-power band extending over only three bins or less, then the frequency of the largest 0·5 Hz bin in this peak never differed by more than one bin from the frequency of the tremor peak in the corresponding force spectrum. When the e.m.g. peak was less well tuned, though still delimitable, there was a regular tendency for the e.m.g. peak to shift in frequency in a similar manner to any shifts in the frequency of the force peak. However, in three of the four experiments in which a full range of spring stiffnesses were used the total range of peak e.m.g. frequencies was slightly less than the corresponding range of the tremor peak frequencies in the force spectra. In addition, the e.m.g. spectra tended to be skewed such that there was commonly a greater spread of the half-power band toward the centre of the range of tremor frequencies seen with the various spring stiffnesses. This suggests that the cyclic neural activity might have tended towards a preferred frequency which was essentially independent of spring stiffness and its effect on the mechanical tuning of the limb. Such a frequency preference could result from either the timing around the stretch reflex arc or a 'repeat tendency' of the motoneuronal pool (Rack, Ross & Walters, 1979).

DISCUSSION

The results of the spectral analysis of force during compliant loading of the arm are largely confirmatory of the findings of Joyce & Rack (1974) and fully support their views on the importance of both the mechanical tuning of the limb and the timing of the stretch reflex for favouring tremor at a particular frequency. In addition, we have examined the tremor during weak elbow flexion in somewhat more detail leaving little doubt that a tremor peak exists for low mean forces, as well as for high, though greatly reduced in amplitude. Our analysis of e.m.g. spectra considerably fortifies the conclusion that reflex action must be involved in the genesis of the vigorous tremor seen at high target forces with compliant loading. A tremor peak was then regularly present in the e.m.g. spectrum but it disappeared when the subject exerted the same force against a rigid restraint. It follows that there was a cyclic modulation of motor discharge in the compliant situation, and that this motor rhythmicity depended upon the occurrence of appreciable movement of the arm. Further, the frequency of the peaks in the force and e.m.g. spectra increased together on increasing the stiffness of the spring against which the arm was flexing. The regular high degree of coherence between the tremor peaks in the e.m.g. and the force spectra demonstrates that the rhythmic electrical activity is phase-locked with the mechanical tremor. It would seem inconceivable that such rhythmic e.m.g. variations could have been produced by a central generator when the arm was loaded compliantly, while the same generator failed to produce a comparable rhythmicity when the arm was rigidly anchored. Rather, the rhythmic motor activity must have resulted from the central action of a similar rhythmicity of afferent input from the moving limb.

The simplest neural mechanism which could underlie the present tremor would be the spinal stretch reflex, as suggested by Joyce & Rack (1974). Unlike the thumb muscles, biceps has a vigorous short-latency spinal stretch reflex in addition to its long loop responses (Marsden, Merton & Morton, 1976). It should be noted that, to produce the tremor, the stretch reflex is required only to alter the fine timing of motor discharges so as to bring a number of units into partial synchrony; the main steady excitatory drive could be provided by descending motor activity. The ability of the stretch reflex to operate over a range of frequencies of tremor on changing the mechanical tuning is of interest, but is not unexpected in view of the likely dispersion of firing of the different afferent fibres and motor units. However, our observation that the frequency of the e.m.g. peak tended to be less affected by altering the spring stiffness than was the frequency of the mechanical tremor peak suggests that the stretch reflex timing caused a preference for a particular oscillatory frequency, typically 9–10 Hz.

At low mean forces, although there was regularly a tremor peak in the force spectrum, no related peak could be detected in the e.m.g. spectrum, thus raising the question whether the tremor was still originating from stretch reflex action. Two alternative possibilities are the occurrence of the unfused tetanic contractions of a number of motor units at the frequency of the observed tremor (Allum, Dietz & Freund, 1978) and the selective effect at the tremor frequency of mechanical resonance introduced by the tuning of the mass-spring system of the compliantly loaded arm. There is no direct evidence to allow the matter to be decided, but the background 'noise' level of the e.m.g. spectrum was such that if there was rhythmic e.m.g. activity associated with the small tremor of low target forces then it would probably not have been resolvable by the present methods. It thus seems a reasonable hypothesis that the small tremor at low target forces was still related to stretch reflex activity, though the additional mechanisms may also have contributed. It bears emphasis that the favourable mechanical tuning of the arm and the sensitivity of the force recording permitted the mechanical detection of small amounts of rhythmic motor activity at the resonant frequency of the system; very little motor synchronisation would be expected to suffice to give the small tremor peaks observed at low mean forces.

In addition, these experiments contribute to the assessment of the utility and limitations of spectral analysis of the gross e.m.g. as a tool in the study of motor function. To begin with, spectral analysis permits more definite conclusions to be reached than would be warranted from simple inspection of records of the raw or rectified e.m.g. In comparison with the study of single motor unit discharges the recording and processing of the surface e.m.g., given the appropriate computing facilities, is much the simpler. Yet in appropriate situations, such as in the present case with large tremor, it can provide definitive evidence for the occurrence of rhythmic motor discharges. On the other hand, it has a limited sensitivity so that a small degree of phased motor activity would seem readily to be lost in the background noise. The noise arises partly from the fact that the gross e.m.g. depends upon the summation of a large number of individual motor unit spike trains each of which will introduce various frequency components into the spectrum. In addition, different units with the same strength but different relative position to the recording electrodes may produce spikes of different sizes. Thus the spectrum of the surface e.m.g. would seem to be limited in its ability to indicate reliably the synchronized firing of the small number of units needed to initiate a measurable tremor occurring at a time when many other units are firing largely at random. Accordingly, in the study of tremor the absence of an appropriate e.m.g. spectral peak cannot be taken to indicate the complete absence of rhythmic neural activity, at least not without a detailed quantitative assessment of the particular situation studied.

We wish to thank P. D. Cussons and J. D. G. Watson for assistance in the preliminary stages of this work and the Nuffield Dominions Trust for an award to R. B. Muir.

REFERENCES

ALLUM, J. H. J., DIETZ, V. & FREUND, H.-J. (1978). Neuronal mechanisms underlying physiological tremor. *J. Neurophysiol.* **41**, 557–571.

BENDAT, J. S. & PIERSOL, A. G. (1971). *Random Data: Analysis and Measurement Procedures.* New York: Wiley-Interscience.

BINGHAM, C., GODFREY, M. D. & TUKEY, J. W. (1967). Modern techniques of power spectrum estimation. *IEEE Trans. Audio & Electroacoustics* **AU-15**, 56–66.

BRIGHAM, E. O. & MORROW, R. E. (1967). The fast Fourier transform. *IEEE Spectrum* **4**, no. 12, 63–70.

CUSSONS, P. D., MATTHEWS, P. B. C. & MUIR, R. B. (1980). Enhancement by agonist or antagonist muscle vibration of tremor at the elastically loaded human elbow. *J. Physiol.* **302**, 443–461.

CUSSONS, P. D., MATTHEWS, P. B. C., MUIR, R. B. & WATSON, J. D. G. (1978). Spectral analysis of tension and of electromyogram during human elbow tremor. *J. Physiol.* **282**, 2–3*P*.

DESMEDT, J. E. (1978). *Progress in Clinical Neurophysiology*, vol. 5. *Physiological Tremor, Pathological Tremors and Clonus*. Basel: Karger.

ELBLE, R. J. & RANDALL, J. E. (1976). Motor-unit activity responsible for 8- to 12-Hz component of human physiological finger tremor. *J. Neurophysiol.* **39**, 370–383.

FOX, J. R. & RANDALL, J. E. (1970). Relationship between forearm tremor and the biceps electromyogram. *J. appl. Physiol.* **29**, 103–108.

JOYCE, G. C. & RACK, P. M. H. (1974). The effects of load and force on tremor at the normal human elbow joint. *J. Physiol.* **240**, 375–396.

JOYCE, G. C., RACK, P. M. H. & ROSS, H. F. (1974). The forces generated at the human elbow joint in response to imposed sinusoidal movements of the forearm. *J. Physiol.* **240**, 351–374.

MARSDEN, C. D., MERTON, P. A. & MORTON, H. B. (1976). Stretch reflex and servo action in a variety of human muscles. *J. Physiol.* **259**, 531–560.

RACK, P. M. H., ROSS, H. F. & WALTERS, D. K. W. (1979). Interactions between the stretch reflex and a 'repeat tendency' of the motoneurone pool in the human. *J. Physiol.* **290**, 21–22*P*.

ROBSON, J. G. (1959). The effect of loading upon the frequency of muscle tremor. *J. Physiol.* **149**, 29–30*P*.